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Enzyme activities in semiarid soils under conservation reserve program, native rangeland, and cropland

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Summary – Zusammenfassung

There is limited knowledge of biochemical processes in low carbon content soils of semiarid regions under different land use and management. This study investigated several enzyme activities of C, N, P, and S transformations in semiarid soils with different clay (10–21 %) and sand (59–85 %) contents that were under conservation reserve program (CRP), native rangeland (NR), and cropland (CL) under sunflowers (*Eriophyllum ambiguum (Gray)*), continuous cotton (*Gossypium hirsutum* L.), or in rotations with wheat (*Triticum aestivum* L.) or sorghum (*Sorghum bicolor* L.) in West Texas, USA. Soils under CRP and NR showed higher total C and N contents than cultivated soils under continuous cotton, but soil pH (6.7–8.4) was not affected by the management or land use studied. The activities of β-glucosidase, β-glucosaminidase, arylamidase, acid and alkaline phosphatase, phosphodiesterase, and arylsulfatase (mg product (kg soil)$^{-1}$ h^{-1}) were lower in CL under continuous cotton compared to cotton in rotation with other crops, CRP, and NR. The enzyme activities were also lower when compared to soils from other regions. Linear regression analyses indicated positive correlations between enzyme activities and total C (*r* values up to 0.96, $P < 0.01$). There was a positive relationship between enzyme activities and total N, but soil pH showed the opposite trend. Enzyme activities were significantly intercorrelated with *r* values up to 0.98 ($P < 0.001$). The specific enzyme activities (mg product (g organic C)$^{-1}$) were lower in continuous cotton in comparison to the uncultivated soils (i.e., NR and CRP) reflecting differences in organic matter quantity and quality due to cultivation. Among the enzymes studied, the specific activities of β-glucosidase and arylamidase showed a more pronounced decrease with increasing soil depth. In general, soils under CRP or wheat-cotton rotations revealed higher enzyme activities than soils under the common agricultural practice for these regions, i.e., continuous cotton under conventional tillage.

Enzymaktivitäten in semiariden Böden unter konservierender Landnutzung, natürlichem Weideland und Ackerland

Begrenzte Informationen liegen über biochemische Prozesse in semiariden Böden unter verschiedenen Landnutzungssystemen vor. In dieser Studie wurden die Aktivitäten von verschiedenen Enzymen des C-, N-, P- und S-Kreislaufes in semiariden Böden mit variierenden Gehalten an Ton (10–21 %) und Sand (59–85 %) unter konservierender Landnutzung (CRP), natürlichem Weideland (NR) und Ackerland untersucht. Innerhalb des Ackerlandes wurden Böden unter Sonnenblumen (*Eriophyllum ambiguum (Gray)*), Baumwoll-Monokulturen (*Gossypium hirsutum* L.), bzw. unter Baumwolle in Fruchtfolge mit Weizen (*Triticum aestivum* L.) oder Hirse (*Sorghum bicolor* L.) beprobt. Böden unter CRP and NR wiesen höhere Gesamtgehalte an C und N auf als Ackerböden unter Baumwoll-Monokultur. Die pH-Werte (pH 6.7–8.4) waren von der Landnutzung unbeeinflusst. Die Aktivitäten von β-Glukosidase, β-Glukosaminidase, Arylaminidase, saurer und alkalischer Phosphatase, Phosphodiesterase und Arylsulfatase (mg Produkt (kg Boden)$^{-1}$ h^{-1}) waren geringer unter Baumwoll-Monokulturen als unter Baumwolle in Fruchtfolge mit anderen Kulturen, CRP und NR. Im Vergleich zu Böden anderer Regionen fielen die Enzymaktivitäten in semiariden Böden geringer aus. Lineare Regressionsanalysen ergaben enge Korrelationen zwischen den Enzymaktivitäten und dem Gehalt an C ($r \leq 0.98$, $P < 0.001$). Die Enzymaktivitäten zeigten positive Beziehungen zum Gesamtgehalt an N und negative Beziehungen zum pH-Wert. Signifikante Interkorrelationen bestanden zwischen den einzelnen Enzymaktivitäten ($r \leq 0.98$, $P < 0.001$). Die spezifischen Enzymaktivitäten (mg Produkt (g organischem C)$^{-1}$) waren geringer unter Baumwoll-Monokultur als unter CRP und NR. Diese Ergebnisse lassen auf nutzungsbedingte Unterschiede in der Quantität und Qualität der organischen Bodensubstanzen schließen. Die spezifischen Aktivitäten von β-Glukosidase und Arylamidase folgten einem stärkeren Tiefengradienten als die anderen Enzymaktivitäten. In der Regel wiesen Böden unter CRP oder Baumwolle in Fruchtfolge mit Weizen und Hirse höhere Enzymaktivitäten auf als Böden unter konventionellen Baumwoll-Monokulturen. Letztere stellen jedoch die übliche landwirtschaftliche Praxis in dieser Region dar.

Key words: specific enzyme activities / arylamidase activity / β-glucosaminidase activity / crop rotations / cotton / sunflowers

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1 Introduction

Soils in semiarid regions have relatively high sand content (> 50 %), low levels of organic matter (as low as 1 %), high pH (alkaline), and generally experience warm temperatures most of the year (avg. 21–27 °C). These factors together represent extreme conditions for biochemical processes, i.e., enzyme activities, compared to soils from other regions. In addition, in semiarid regions like Texas High Plains (West Texas), USA, the degradation of organic matter may exceed the rate of humus synthesis in cropland due to the production of low residue crops such as cotton (*Gossypium hirsutum*) in monoculture under conventional tillage. Thus, the Conservation Reserve Program (CRP) may provide a sustainable option for the soils of this region because it focuses on returning highly eroded land (HEL) to grass and forest vegetation according to the Food Security Act in 1985. CRP should impact soil C sequestration of atmospheric CO_2 as well as other soil processes. Little attention, however, has been paid

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to the status of soil enzyme activities in semiarid regions as a function of land use and management. This information will allow the selection of more sustainable systems, and to develop more environmentally sustainable and economically feasible cropping systems that assure the viability of agricultural activities in the semiarid soils of Texas High Plains.

Enzyme (hydrolytic extracellular) activities can provide information on important biochemical processes of soil (i.e., degradation potential) (*Trasar-Cepeda* et al., 2000) that affect soil function. The assessment of enzyme activities is simple, requires low labor costs compared to other biological analysis (*Ndiaye* et al., 2000), and the results are correlated to other soil properties (*Klose* et al. 1999; *Moore* et al., 2000; *Ndiaye* et al., 2000; *Trasar-Cepeda* et al., 2000). Further, enzyme activities have the potential to anticipate changes in soils before they are detected by other soil properties (*Ndiaye* et al., 2000). Previous studies with soils from various regions have shown that enzyme activities are significantly affected by tillage (*Kandeler* et al., 1999; *Acosta-Martínez* and *Tabatabai*, 2001), cropping systems (*Bandick* and *Dick*, 1999; *Klose* et al., 1999; *Ndiaye* et al., 2000; *Ekenler* and *Tabatabai*, 2002), and land use, including the recently implemented Conservation Reserve Program (CRP) (*Staben* et al., 1997; *Gewin* et al., 1999; *Landgraf* et al., 2001; *Landgraf* and *Klose*, 2002).

The objective of this study was to investigate the status of several enzyme activities involved in C, N, P, and S cycling in semiarid soils under different land use and soil management practice, water management, and carbon input such as CRP, native rangeland (NR), and cropland. The β-glucosidase activity was studied because it is involved in the last limiting step of cellulose degradation (C cycle). Arylsulfatase activity was studied because this enzyme is used to investigate organic S mineralization in soils. The enzymes β-glucosidase and arylsulfatase play a critical role in organic matter decomposition and mineralization in soils, and are sensitive to soil management (*Bandick* and *Dick*, 1999; *Ndiaye* et al., 2000). Little is known about chitin degradation in semiarid soils, and thus, the recently detected β-glucosaminidase activity (*Parham* and *Deng*, 2000) was studied because it is a key enzyme involved in the hydrolysis of N-acetyl-β-D-glucosamine residue from the terminal non-reducing ends of chitooligosaccharides. This hydrolysis is considered to be important in C and N cycling in soils because it participates in the processes whereby chitin is converted to amino sugars, a major source of mineralizable N in soil (*Stevenson*, 1994; *Ekenler* and *Tabatabai*, 2002). Little is known about the contribution of enzyme activities to the degradation of organic matter in semiarid soils, and thus, arylamidase activity was investigated as it catalyzes the release of amino acids from organic matter. This reaction represents the initial step of the mineralization of amino acids in soil. Arylamidase and β-glucosaminidase activities have been positively correlated with the cumulative N mineralized in soils (*Dodor* and *Tabatabai*, 2002; *Ekenler* and *Tabatabai*, 2002). The phosphatases (alkaline phosphatase, acid phosphatase, and phosphodiesterase) were studied because they are significantly affected by soil pH, which controls phosphorus availability, despite of organic matter content or levels of disturbance.

2 Materials and methods

2.1 Soil sampling and sites description

The soils studied were located in Crosby, Cochran, Lubbock, and Hockley County in West Texas, USA. This region generally has an annual mean precipitation of 457 mm and an annual mean temperature that ranges from 21 to 27 °C. The soils showed a wide range in their chemical properties at 0 to 5 cm (Tab. 1). The pH values varied in the top 5 cm depth from 6.7 to 8.4, total C from 2.81 to 18.74 g (kg soil)$^{-1}$, and total N from 0.27 to 1.50 g (kg soil)$^{-1}$ (Tab. 1).

Samples were taken in January 2001 from an Amarillo soil (Fine, mixed, thermic, superactive, Aridic Paleustalf), an Estacado loam (Fine, mixed, thermic, superactive, Aridic Paleustolls), an Acuff soil (Fine-loamy, mixed, thermic, superactive, Aridic Paleustolls), and a Patricia soil (Loamy, mixed, superactive, thermic Arenic Aridic Paleustalfs) under Conservation Reserve Program (CRP), Native Rangeland (NR), and cropland (CL). Samples were collected from 0–5 cm soil depth, and from depths of 0–5, 5–10, 10–15, and 15–30 cm of the Estacado soil by using a 4.08 cm diameter split-barrel Giddings probe. Each sample is a composite mixture of five cores. In systems with row crops, the cores were collected 20 cm apart in the direction perpendicular to tillage.

The CRP sites were established in 1991, when planted with WW spar bluestem (*Bothriochloa ischaemum*), blue grama (*Bouteloua gracilis*), and green sprangletop (*Leptochloa dubia*). The plant community at the NR sites was 80 % blue grama (*Bouteloua gracilis*), 5 % buffalo grass (*Buchloe dactyloides*), 5 % common curly mesquite (*Hilaria belangeri*), and other less predominant grasses. The sites under continuous cotton (*Gossypium hirsutum* L.) were under conventional tillage either irrigated or in dryland. Other sites studied were under cotton and wheat (*Triticum aestivum* L.) or sorghum (*Sorghum bicolor* L.) rotations (dryland) under conservation tillage (reduced tillage). The sites under CL were generally under the indicated management for more than 5 years. In addition, we studied a site in the first year under irrigated sunflowers (*Eriophyllum ambiguum (Gray)*) (under conservation tillage), that was previously under CRP for 9 years (Tab. 1).

For continuous cotton, dryland or irrigated, under conventional tillage, the cotton stalks were shredded and disked in December, chisel plowed in February, and herbicide incorporated with a spring-tooth chisel followed by listing in March, and rod-weeding before planting in early May. After planting in May, a rotary hoe was used for wind erosion control and to break the crust after rain events in May and June. Field cultivation was done in June and July. The sites under cotton and wheat rotations, under conservation tillage, had cotton planted into previous wheat crop residue.

For convenience, abbreviations (parentheses) will be used for Conservation Reserve Program (CRP), native rangeland (NR), cropland (CL), cotton (Ct), wheat (W), sunflowers (Sf), sorghum (Sr), dryland (Dry), irrigated (Irrig), conservation tillage (Cs), and conventional tillage (Cv).

Table 1: Selected properties of the semiarid soils studied at 0–5 cm depth.
Tabelle 1: Ausgewählte Eigenschaften der untersuchten semiariden Böden in 0–5 cm Bodentiefe.

Soil	Classification	Treatments[a]	Texture			Soil chemical properties		
			Clay	Silt	Sand	pH[b]	Total C	Total N
			— % —				— g kg^{-1} —	
Patricia	USDA: Loamy, mixed, superactive, thermic Arenic Aridic Paleustalfs		10	5	85			
		Ct-Ct/Dry/Cv				8.1	2.81	0.38
	FAO:	Ct-Ct/Irrig/Cv				8.1	3.40	0.45
	Calcic Luvisols	Ct-W/Dry/Cs				7.4	2.78	0.24
		CRP				7.3	4.01	0.27
		NR				–	–	–
Amarillo	USDA: Fine-loamy, mixed, thermic, superactive, Aridic Paleustalfs		15	14	71			
		Ct-Ct/Dry/Cv				6.8	3.13	0.45
	FAO:	Ct-Ct/Irrig/Cv				7.5	3.61	0.45
	Calcic Luvisols	W-Ct/Dry/Cs				7.5	5.78	0.47
		CRP				6.7	11.30	1.10
		NR				6.7	14.07	0.98
Acuff	USDA: Fine-loamy, mixed, thermic, superactive, Aridic Paleustolls		20	19	61			
		Ct-Ct/Dry/Cv				8.0	3.80	0.30
	FAO:	Ct-Ct/Irrig/Cv				8.6	3.18	0.36
	Luvic Kastanozems	Ct-Sr/Dry/Cs				8.0	7.68	0.72
		CRP				8.2	11.24	0.82
		NR				7.9	18.74	1.50
Estacado	USDA: Fine, mixed, thermic, superactive, Aridic Paleustolls		21	20	59			
		Ct-Ct/Dry/Cv				8.4	6.65	0.55
	FAO:	Ct-Ct/Irrig/Cv				7.6	6.95	0.62
	Luvic Kastanozems	W-Ct/Dry/Cs				7.1	8.93	1.03
		Sf/Irrig/Cs				7.6	9.06	0.67
		CRP				7.6	13.18	0.73
		NR				7.5	11.10	0.85

[a] For an agricultural soil under rotation, samples were taken after the second crop. Ct = Cotton; W = Wheat; Sr = Sorghum; Sf = Sunflowers; CRP = Conservation Reserve Program; NR = Native Rangeland; Dry = Dryland; Irrig = Irrigated; Cs = Conservation tillage; Cv = Conventional tillage.
[b] The pH was determined in a soil:water ratio of 1:2.5.

2.2 Soil analyses

The pH values were measured on air-dried soil (< 2 mm) using a glass combination electrode (soil:water ratio, 1:2.5). Subsamples (air-dried) were ground to pass an 80-mesh (180 μm) sieve for analyses of organic C and total N by the Vario Max-ELEMENTAR CN-analyzer (D-63452 Hanau; Germany)[1].

The activities of β-glucosidase, β-glucosaminidase, arylamidase, alkaline and acid phosphatase, phosphodiesterase, and arylsulfatase were assayed using 1 g of soil (< 2 mm, air-dried) and incubated for 1 hour with their substrate at their optimal pH. The assay procedures have been described elsewhere: β-glucosaminidase activity (*Parham* and *Deng*, 2000), arylamidase activity (*Acosta-Martínez* and *Tabatabai*, 2000a), and the other enzyme activities (*Tabatabai*, 1994). Enzyme activities were assayed in duplicates and one control to which the substrate was added after stopping the reaction. The results are expressed as the mg of *p*-nitrophenol (PN) released (kg soil)$^{-1}$ (moisture-free basis) h^{-1} for all the enzymes, except for arylamidase activity, which is expressed as the mg of β-naphthylamine (NA) released (kg soil)$^{-1}$ (moisture-free basis) h^{-1}. The specific activities of the enzymes studied were expressed per unit organic carbon (mg product (g organic C)$^{-1}$) according to previous work (*Dodor* and *Tabatabai*, 2002; *Klose* and *Tabatabai*, 2002a, b).

2.3 Statistical analyses

Statistical analyses, including analysis of variance (ANOVA), multivariate analysis of variance (MANOVA), contrast comparisons and separation of means by least significant differences (LSD), were performed by using the general linear model procedure of the Statistical Analysis System (*SAS*, 1999).

[1] Trade names and company names are included for the benefit of the reader and do not infer any endorsement or preferential treatment of the product by USDA-ARS.

3 Results and discussion

3.1 Effects of soil management

In the semiarid soils studied, enzyme activities were decreased by cultivation under cotton-cotton (irrigated or dryland under conventional tillage) compared to uncultivated systems such as NR and CRP (Fig 1). For example, acid and alkaline phosphatase activities were 3 to 15 times lower in CL under cotton-cotton (either irrigated or dryland under conventional tillage) than in soils under NR and CRP (Tab. 2, 4). The lower soil enzyme activities in cotton-cotton (irrigated or dryland under conventional tillage) could be attributed to a lack of crop residue cover during winter and spring periods in comparison to CRP and NR. The results of the enzyme activities also demonstrate the positive impact of a more continuous rhizosphere and the absence of tillage on the microbial populations and activities in semiarid soils. The response of the phosphatases could be also due to the lack of P fertilization in the uncultivated systems. Lower enzyme activities were also reported in cultivated soils in semiarid regions in Spain, in particular under monoculture cropping systems, when compared to the corresponding native soils (*Pascual* et al., 1999). The results agree with a study on silt loams were enzyme activities, soil N, C mineralization potential, and active bacterial biomass were greater in CRP after 4 to 7 y than in a wheat-fallow system (*Staben* et al., 1997).

The soils used in this study were under the management and land use system for more than 5 years, but the Estacado soil was also evaluated after the first year of cultivation with sunflower of a previous CRP land. This allowed an evaluation of the status of enzyme activities after a sudden change in land use and management. In this soil, one year of cultivation of CRP with irrigated sunflowers under conservation tillage caused a rapid decrease in organic C content and in the activities of β-glucosidase, β-glucosaminidase, acid phosphatase, alkaline phosphatase, phosphodiesterase, and arylsulfatase compared to CRP (0–5 cm depth) (Tab. 2). These results are only for one of the soils studied, but agree with the rapid loss of soil microbial biomass found after the cultivation of an undisturbed land (*Haines* and *Uren*, 1990), which may have also been reflected by soil enzyme activities. Because the enzyme activities studied play important roles in key biochemical reactions of element transformations in soils, the results support the finding that altering the native vegetation through cropping systems can result in degraded soils (*Dick*, 1997).

Surprisingly, for these typical soils of semiarid regions, even though it had less total C than either NR or CRP, rotations of cotton with wheat or sorghum under conservation tillage had similar enzyme activities compared to NR or CRP (Tab. 1, 2). These results are correlated to previous studies reporting a faster response of enzyme activities than organic matter in soils (*Acosta-Martinez* et al., 2003). They also show that crop rotations and conservation tillage can restore some biochemical processes comparable to native systems for semiarid soils.

Among the cropland evaluated, enzyme activities were lower in cotton-cotton (irrigated or dryland) under conventional tillage compared to the crop rotations under conservation tillage while there were no differences in total C and N contents between these systems (Tab. 2, 4). These results are related to the higher residues incorporated in soil under the crop rotations than under monoculture systems. A long-term study showed that cotton grown every year without a winter legume

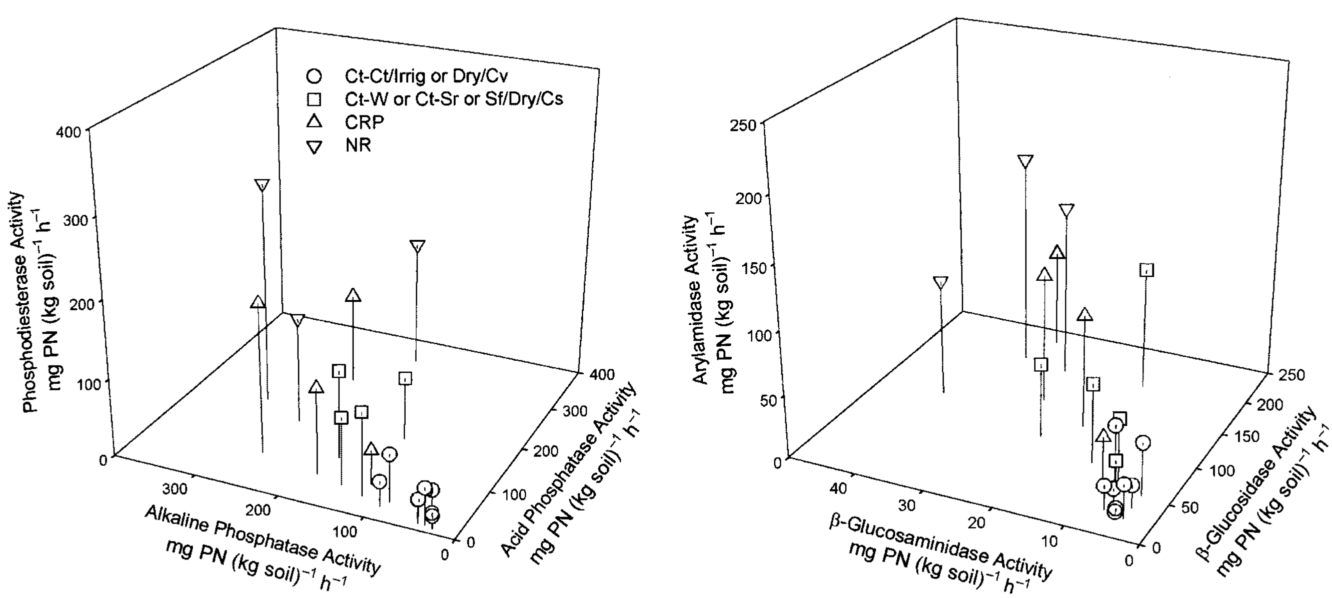

Figure 1: Enzyme activities in typical soils (0–5 cm depth) of the semiarid regions of West Texas, USA as affected by land use and management. The plots of acid and alkaline phosphatase and phosphodiesterase activities have a different scale (A), relative to the plots of arylamidase, β-glucosidase, and β-glucosaminidase activities (B).

Abbildung 1: Enzymaktivitäten in typischen Böden (0–5 cm Tiefe) der semiariden Gebiete in Westtexas, USA unter dem Einfluss von Landnutzungssystemen. Die Abbildungen für die Aktivitäten von saurer und alkalischer Phosphatase, und Phosphodiesterase weisen eine andere Skalierung (A) auf als jene für Arylamidase-, β-Glukosidase- und β-Glukosaminidaseaktivitäten (B).

Table 2: Enzyme activities as affected by different managament and land use in the semiarid soils studied at 0–5 cm depth.
Tabelle 2: Enzymaktivitäten in semiariden Böden unter dem Einfluss von unterschiedlichen Landnutzungsystemen in 0–5 cm Bodentiefe.

Series[a]	Enzyme Activities						
	β-Glucosidase	β-Glucosaminidase	Arylamidase	Phosphatase		Phosphodiesterase	Arylsulfatase
				Acid	Alkaline		
	mg product released (kg soil)$^{-1}$ h^{-1}						
Patricia							
Ct-Ct/Dry/Cv	22	5	5	9	28	17	2
Ct-Ct/Irrig/Cv	23	5	7	10	29	20	2
Ct-W/Dry/Cs	46	7	28	32	46	32	9
CRP	49	9	42	63	120	44	25
NR	–	–	–	–	–	–	–
Amarillo							
Ct-Ct/Dry/Cv	28	7	19	49	45	21	11
Ct-Ct/Irrig/Cv	23	4	27	36	47	28	9
W-Ct/Dry/Cs	78	13	63	47	147	88	13
CRP	121	18	90	58	181	111	25
NR	124	40	93	345	190	164	34
Acuff							
Ct-Ct/Dry/Cv	37	4	18	12	38	48	11
Ct-Ct/Irrig/Cv	31	6	16	13	45	31	13
Ct-Sr/Dry/Cs	63	8	50	37	119	107	23
CRP	144	26	103	73	256	193	53
NR	198	34	166	185	308	285	58
Estacado							
Ct-Ct/Dry/Cv	53	4	42	25	93	33	3
Ct-Ct/Irrig/Cv	57	8	48	38	88	62	4
W-Ct/Dry/Cs	192	15	98	98	174	114	8
Sf/Irrig/Cs	96	22	59	167	127	81	5
CRP	231	32	78	270	238	117	15
NR	191	27	136	154	251	137	13

[a] Ct = Cotton; W = Wheat; Sr = Sorghum; Sf = Sunflowers; CRP = Conservation Reserve Program; NR = Native Rangeland; Dry = Dryland; Irrig = Irrigated; Cs = Conservation tillage; Cv = Conventional tillage.

or N fertilizer had lower amounts of soil organic matter, microbial biomass C and N, and cotton seed yield in comparison to cotton in 2-year rotations with corn (*Zea mays* L.) with a winter cover crop such as clover (*Trifolium incarnatum* L.) or in 3-year rotation with corn and rye (*Secale cereale* L.) with the clover winter cover crop (*Entry* et al., 1996). A study in the Texas High Plains region showed that cotton-wheat rotations had greatest positive effect on cotton yield in comparison to continuous cotton, and found the greatest cotton lint yield (20–25 % increases) when no-tillage was combined with the cotton-wheat rotation (*Bordovsky* et al., 1994). Cotton-cotton (irrigated or dryland) under conventional tillage sustained also lower enzyme activities in comparison to irrigated sunflowers under conservation tillage, which is caused by the differences in vegetation and tillage practices. These differences are not related to the CRP history of the soils under sunflowers because organic C at 0 to 5 cm depth was already decreased after one year of returning CRP to cultivation. These differences are not related to irrigation of sunflowers either because the enzyme activities of cotton-cotton (irrigated or dryland under conventional tillage) were not significantly affected by irrigation, except for phosphodiesterase activity.

The results of this study agree with the higher microbial biomass and enzyme activities reported in crop rotations compared to continuous (monoculture) systems (*Entry* et al., 1996; *Klose* et al., 1999; *Ekenler* and *Tabatabai*, 2002; *Dodor* and *Tabatabai*, 2002; *Acosta-Martínez* et al., 2003). In agreement to our findings, *Ndiaye* et al. (2000) reported an increase in β-glucosidase and arylsulfatase activities in cover crop plots compared to winter fallow, and it was found that the increases in enzyme activities were correlated to microbial biomass C. β-glucosaminidase and arylsulfatase activities have been proposed as indirect indicators of soil fungal biomass (*Miller* et al., 1998; *Bandick* and *Dick*, 1999). Because any reduction in tillage favors existing fungi hyphae network expansion in soils, increases in these two enzyme activities in crop rotations and conservation tillage systems may be indicative of higher fungi populations, and thus, total microbial biomass in comparison to continuous cotton under conventional tillage. Higher arbuscular mycorrhizal colonization was found in soils from the same semiarid region under wheat-cotton rotations than in continuous cotton (*Zak* et al., 1998).

3.2 Specific enzyme activities as affected by land use, management, and soil depth

Enzyme activities are generally reported as the mg of product (kg of soil)$^{-1}$ h^{-1} (*Tabatabai*, 1994). It has been suggested that the calculation should be based on nutrient equivalents as the mg nutrient kg soil unit^{-1} time^{-1} for those assays that measure *p*-nitrophenol as the product (*Dick* et al., 1996). We calculated the specific enzyme activities, which is a recent approach to account for the enzyme activity per unit of organic C in soil (*Dodor* and *Tabatabai*, 2002). A high sensitivity of specific enzyme activities to crop rotations has been reported for soils with high contents of organic matter and clay (*Klose* et al., 1999; *Dodor* and *Tabatabai*, 2002; *Ekenler* and *Tabatabai*, 2002). To our knowledge, no data have been documented of the enzyme activities per unit of soil organic C for low carbon content soils of semiarid regions. According to *Ekenler* and *Tabatabai* (2002), the specific activities could provide a C quality index.

The specific activities of β-glucosidase and arylsufatase were higher in CRP, NR, and dryland wheat-cotton under conservation tillage than in cotton-cotton soils in the Estacado soil at 0–5 cm soil depth (Tab. 3). The specific activity of β-glucosaminidase was higher in all the systems compared to cotton-cotton soils. The specific activity of alkaline phosphatase was higher in dryland wheat-cotton under conservation tillage and NR compared to the cotton-cotton system. The specific activities of phosphodiesterase and acid phosphatase were significantly higher in all the systems than in dryland cotton-cotton under conventional tillage. Generally, the specific activities reflected the differences in the organic C contents within the systems studied, and the same could be expected for the other soils (Tab. 1).

We were also interested in the response of the specific activity of arylamidase to the management systems studied because this enzyme was just recently detected in soils and plays an important role in the N mineralization (*Acosta-Martínez* and *Tabatabai*, 2000a). The specific activity of arylami-

Table 3: Chemical properties and specific activities of enzymes in the Estacado loam with increasing soil depth as affected by land use and management.

Tabelle 3: Chemische Eigenschaften und spezifische Enzymaktivitäten im Estacado Lehmboden in unterschiedlicher Bodentiefe unter dem Einfluss von verschiedenen Landnutzungsystemen.

System[a]	Depth	pH[b]	Organic C	Total N	Specific Enzyme Activities						
					β-Glucosidase	β-Glucosaminidase	Arylamidase	Phosphatases		Phosphodiesterase	Arylsulfatase
								Acid	Alkaline		
	cm		— g kg^{-1} —		mg p-Nitrophenol (g organic C)$^{-1}$		mg β-Napthylamine (g organic C)$^{-1}$	— mg p-Nitrophenol (g organic C)$^{-1}$ —			
Ct-Ct/Dry/Cv											
	0–5	8.4	6.60	0.55	8.0	0.6	6.3	3.7	14.0	5.0	0.5
	5–10	–	7.10	0.60	–	–	–	–	–	–	–
	10–15	8.2	6.00	0.56	4.2	0.7	3.0	4.2	11.3	4.1	1.0
	15–30	8.3	6.10	0.36	2.3	0.7	4.1	5.1	9.8	3.4	1.1
Ct-Ct/Irrig/Cv											
	0–5	7.6	6.90	0.62	8.2	1.1	6.9	8.3	16.5	8.9	0.6
	5–10	–	7.90	0.62	4.8	1.1	–	7.2	13.0	10.0	1.0
	10–15	8.0	7.60	0.66	3.4	1.5	4.3	6.6	12.0	8.2	1.3
	15–30	8.3	8.00	0.67	1.6	1.1	3.8	4.8	11.0	6.6	1.1
W-Ct/Dry/Cs											
	0–5	7.1	8.90	1.03	21.6	3.3	10.9	11.0	19.5	12.9	1.3
	5–10	7.6	8.80	1.03	9.1	1.4	–	9.3	11.6	6.3	0.9
	10–15	7.6	8.30	0.65	6.1	0.9	3.7	9.9	7.5	5.5	0.8
	15–30	7.8	7.00	0.76	3.0	0.9	3.3	5.9	7.0	5.9	0.9
Sf/Irrig/Cs											
	0–5	7.1	8.90	0.63	10.7	2.5	6.6	18.7	14.2	9.1	0.8
	5–10	7.7	7.70	0.50	7.4	2.0	5.3	22.3	13.4	10.3	1.6
	10–15	7.7	7.60	0.56	4.0	2.2	3.8	18.4	11.7	11.1	1.8
	15–30	7.6	6.60	0.44	2.4	1.8	4.4	13.5	10.9	12.9	1.7
CRP											
	0–5	7.6	13.10	0.73	17.7	2.5	5.9	20.5	18.2	8.9	2.3
	5–10	7.6	9.00	0.67	7.8	2.2	6.3	20.1	16.3	9.0	1.7
	10–15	7.5	7.70	0.66	3.6	1.8	5.1	15.3	13.9	8.6	1.6
	15–30	7.7	8.40	0.63	1.9	2.0	4.5	11.0	15.6	8.2	1.4
NR											
	0–5	7.5	11.00	0.85	15.6	2.3	12.3	14.0	22.8	12.4	2.0
	5–10	8.1	9.40	0.51	5.9	2.0	5.9	10.3	17.8	9.4	1.5
	10–15	7.9	7.40	0.61	3.8	1.5	4.5	7.2	12.4	6.9	1.4
	15–30	7.8	8.00	0.44	2.8	1.0	4.8	7.4	13.5	7.6	1.8
LSD $P < 0.05$	0–5				5.6	1.1	3.2	7.1	8.4	3.7	0.5

[a] Ct = Cotton; W = Wheat; Sf = Sunflowers; CRP = Conservation Reserve Program; NR = Native Rangeland; Dry = Dryland; Irrig = Irrigated; Cs = Conservation tillage; Cv = Conventional tillage.

[b] The pH was determined in a soil:water ratio of 1:2.5. In some cases, sample was not available (–).

Table 4: Probability levels (P values) of the multivariate analyses of variance for the enzyme activities and chemical properties investigated in the soils studied.
Tabelle 4: Wahrscheinlichkeitswerte (P-Werte) der multivariaten Varianzanalyse von Enzymaktivitäten und chemischen Eigenschaften der untersuchten Böden.

Source of variation[a]	Enzyme activities									
	β-Glucosidase	β-Glucosaminidase	Arylamidase	Phosphatase		Phosphodiesterase	Arylsulfatase	Soil pH	Total C	Total N
				Acid	Alkaline					
C1 vs. C2	0.0360	0.0359	0.0150	n.s[b]	0.0131	0.0496	n.s	n.s	n.s	n.s
C1 vs. C3	0.0025	0.0004	0.0015	0.0343	0.0001	0.0057	0.0058	n.s	0.0221	n.s
C1 vs. C4	0.0005	0.0001	0.0001	0.0003	0.0001	0.0001	0.0025	n.s	0.0001	0.0016
C1 vs. C2 vs. C3 vs. C4	0.0016	0.0001	0.0001	0.0023	0.0001	0.0003	0.0049	n.s	0.001	0.0119

[a] C1 vs. C2 = CtCt/Dry/Cv vs. (W-Ct/Dry/Cs, Sf/Irrig/Cs, Ct-W/Dry/Cs, Ct-Sr/Dry/Cs); C1 vs. C3 = CtCt/Dry/Cv vs. CRP; C1 vs. C4 = CtCt/Dry/Cv vs. NR.
[b] n.s.= not significant.

dase at 0–5 cm soil depth varied between 5.9 and 12.3 mg NA (g organic C)$^{-1}$ depending on the management. NR and cotton in rotation with wheat under conservation tillage had the highest specific activity of this enzyme compared to the other systems, indicating higher N mineralization potential in these systems.

The specific activities decreased with soil depth, but the specific activities of β-glucosidase and arylamidase showed more pronounced decreases with soil depth than the other enzymes (Tab. 3). Specific activities at 0–5 cm soil depth were more than 1.5-fold higher than at 15–30 cm depth. Decreases in several enzyme activities within the soil profile have been reported for different soils, and are correlated to the decreases in organic C content (*Deng* and *Tabatabai*, 1996a, b, 1997; *Dick*, 1997; *Acosta-Martínez* et al., 1999; *Acosta-Martínez* and *Tabatabai*, 2001; *Landgraf* and *Klose*, 2002).

3.3 Relationships of enzyme activities and soil properties

The relationship among soil properties and enzyme activities was investigated for the Estacado soil. Linear regression analysis showed a trend of a negative relationship between enzyme activities and soil pH at 0 to 5 cm depth (Tab. 5). These findings will apply for the other soils, too, because typically semiarid soils show pH values of above 7, except for the Amarillo soils under CRP and NR. In a study on a Kenyon loam (fine-loamy, mixed, mesic Typic Hapludoll) soil in the humid region of Iowa, USA, the activities of fourteen different enzymes, except acid phosphatase, were positively correlated to soil pH values that ranged from 4.9 up to 6.9 (*Acosta-Martínez* and *Tabatabai*, 2000b). The decrease in the enzyme activities, except for alkaline phosphatase, with increasing soil pH beyond pH 7 is believed to be due to a reduction in the ionization and solubility of enzymes, substrates, and cofactors in soils.

Enzyme activities were positively correlated with organic C and total N. These results were significant for the relationships between the activities of β-glucosidase, β-glucosaminidase, acid phosphatase, alkaline phosphatase, arylsulfatase and organic C (Tab. 5). The partially ambiguous relationships between the enzyme activities and total N could be related to the low organic matter contents of semiarid soils. Enzyme activities have been shown to correlate with organic C, total N, and clay contents in soils in the humid and moderate climate zones (*Tabatabai*, 1994; *Deng* and *Tabatabai*, 1996b, 1997; *Acosta-Martínez* and *Tabatabai*, 2001; *Landgraf* and *Klose*, 2002).

The enzyme activities were significantly intercorrelated with r values up to 0.98 ($P < 0.001$). The intercorrelations between the enzyme activities studied indicate that the enzymes responded similarly to the studied management and land use systems. In addition, it may indicate that these enzymes have similar origin and persistence in soil (*Bandick* and *Dick*, 1999). The responses of enzyme activities to the management was similar for the different soils studied, indicating that these results can be applied to other semiarid soils (Fig. 1, Tab. 4).

3.4 Comparison of enzyme activities with different vegetation and soils

The enzyme activities were generally lowest in the Patricia soil because it contained the lowest clay content (10 %) and highest sand content (85 %) among the soils. In addition, this soil contains the lowest total C and N contents among the soils. Alkaline phosphatase, acid phosphatase, and β-glucosidase activities were higher than β-glucosaminidase, phosphodiesterase, arylamidase, and arylsulfatase activities in the soils studied (Tab. 2). Irrespective of the management system, alkaline phosphatase activity was more than 2-fold higher than the least predominant enzymes β-glucosaminidase and arylsulfatase (Tab. 2). Alkaline phosphatase activity in cotton-cotton (irrigated or dryland under conventional tillage) and cotton in rotations with wheat or sorghum under conservation tillage at 0–5 cm depth of the Aridic Paleustolls or Aridic Paleustalfs studied, was lower than the values

Table 5: Correlation coefficients (r) between soil chemical properties and enzyme activities in the Estacado soil (n = 18).
Tabelle 5: Korrelationskoeffizienten (r) für die Beziehungen zwischen chemischen Eigenschaften und Enzymaktivitäten im Estacado Boden (n = 18).

Parameter[a]	β-Glucosidase	β-Glucosaminidase	Arylamidase	Phosphatase		Phosphodiesterase	Arylsulfatase	Soil pH	Organic C	Total N
				Acid	Alkaline					
β-Glucosidase		0.94**	0.70	0.77	0.89*	0.81*	0.91**	–0.44	0.89*	0.73
β-Glucosaminidase			0.67	0.82*	0.81*	0.83*	0.81*	–0.69	0.86*	0.72
Arylamidase				0.38	0.85*	0.90*	0.73	–0.42	0.61	0.78
Acid Phosphatase					0.75	0.63	0.82*	–0.43	0.94**	0.21
Alkaline Phosphatase						0.90*	0.98***	–0.32	0.92**	0.60
Phosphodiesterase							0.83*	–0.64	0.76	0.75
Arylsulfatase								–0.25	0.96**	0.50

[a] *= $P < 0.05$, **= $P < 0.01$, ***= $P < 0.001$.

reported for other agricultural soils (Tab. 2). For example, according to a recent review article by *Emmerling* et al. (2002), alkaline phosphatase activities from the top 15 cm depth of different types of vegetation and soils, varied considerably and revealed values of 40–80 mg PN (kg soil)$^{-1}$ h^{-1} in grassland/Pachic Arguistoll (*Ajwa* et al., 1999), 40–790 mg PN (kg soil)$^{-1}$ h^{-1} in agricultural land/Aeric Vertic Epiaqualfs (*Kim* et al., 1998), 100–500 mg PN (kg soil)$^{-1}$ h^{-1} under crop rotations/Hapludalf (*Deng* and *Tabatabai*, 1997), and 181–225 mg PN (kg soil)$^{-1}$ h^{-1} under crop rotations/Ustochrept (*Chander* et al., 1997). Values for NR are within the range reported for other grassland systems (*Emmerling* et al., 2002). Alkaline phosphatase activities of the CRP system revealed intermediate values compared to those values reported in the literature.

The activities of phosphodiesterase and acid phosphatase in the top 0–5 cm were similar than corresponding enzyme activity values reported for the top 0–15 cm of a Typic Hapludoll (pH up to 6.9) under agricultural practice in Iowa, USA (*Acosta-Martínez* and *Tabatabai*, 2000b). The values of β-glucosidase activity at 0–5 cm soil depth were lower than values reported for the 0–15 cm depth in other agricultural soils (*Emmerling* et al., 2002). Arylamidase activity at the top 5 cm of soil under continuous cotton and conventional tillage was similar to the values reported for the top 15 cm depth of a Typic Hapludalf under continuous corn and conventional tillage of the humid climate zone in Iowa, USA (*Acosta-Martínez* and *Tabatabai*, 2001). Arylsulfatase activity is usually the enzyme with the lowest levels in soils (*Tabatabai*, 1994). The values of this enzyme activity in the top 5 cm of the soil studied were more than 5 times lower than the values reported for the top 15 cm of a Typical Hapludoll under similar management (*Klose* et al., 1999). Our results are in agreement with *García* et al. (1994) who found lower enzyme activities in semiarid regions of Spain than those reported from more humid regions.

4 Conclusions

The results provide information on important enzyme activities involved in soil biogeochemical cycling that should be taken into consideration in management decisions of semiarid regions in order to select sustainable alternatives. The set of enzymes used in this study was sensitive to soil management and responded similarly. CRP increased the soil biochemical reactions studied in comparison to continuous cotton, suggesting that CRP contributes to the restoration of the nutrient cycling potential and organic matter turnover in agricultural soils. The results also showed that cotton in rotations with wheat or sorghum sustained higher enzyme activities than cotton-cotton, while total C and N remained unchanged. Thus, crop rotation appears to be an effective alternative management practice for agricultural soils of this region, most likely due to greater and more diverse crop residues of these systems. In contrast, continuous cotton under conventional tillage was the least desirable system as reflected in lower enzyme activities and organic matter content compared to more diverse crop rotations.

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